

A Mechanical Cryogenic Cooler for the Hubble Space Telescope

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Abstract

This paper presents a description of the Hubble Space Telescope (HST) Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) Cryo Cooler (NCC), the cutting edge technology involved, its evolution, performance, and future space applications. The NCC is the primary hardware component of the NICMOS Cooling System comprised of the NCC, an Electronics Support Module, a Capillary Pumped Loop/Radiator, and associated interface harnessing. The system will be installed during extravehicular activities on HST during Servicing Mission 3B scheduled for launch in February 2002. The NCC will be used to revive the NICMOS instrument, which experienced a reduced operational lifetime due to an internal thermal short in its dewar structure, and restore HST scientific infrared capability to operational status. The NCC is a state-of-the-art reverse Turbo-Brayton cycle cooler employing gas bearing micro turbo machinery, driven by advanced power conversion electronics, operating at speeds up to 7300 revolutions per second (rps) to remove heat from the NICMOS instrument.

Technology Development

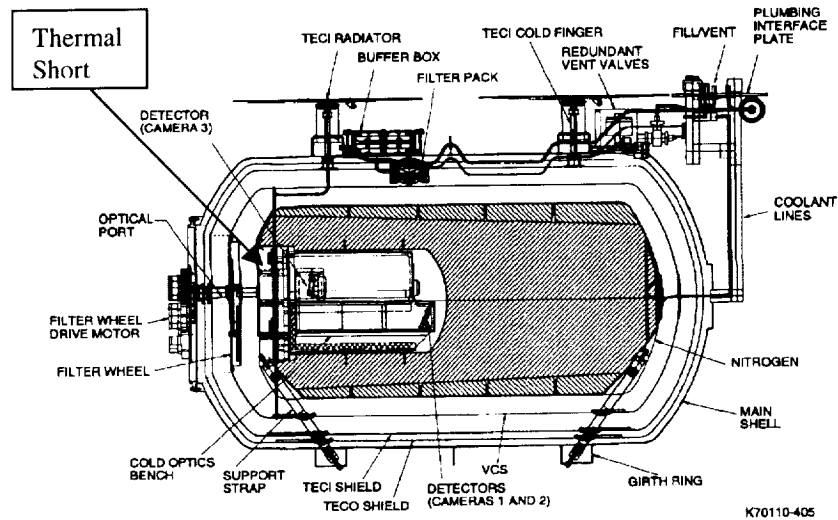
NICMOS Application

The Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) instrument was installed via extravehicular activities (EVA), during Hubble Space Telescope (HST) Servicing Mission 2 (SM2), replacing the Goddard High Resolution Spectrograph in Bay 2 of the Aft Shroud. NICMOS provides the only Infrared (IR) imaging capability on HST through the use of three cameras mounted to a cold optics bench enclosed in a solid nitrogen/aluminum foam dewar that maintains the cameras at 58 K with a stability of ± 2 K. Three thermal shields surround the dewar to provide cooling: the Vapor Cooled Shield (VCS), the Thermo Electric-Cooled Inner Shield, and the Thermo Electric-Cooled Outer Shield. Following installation, an unexpected heat load (422 milli-watts) was identified that reduced the dewar lifetime from a projected 60 months to an actual operation of 22 months. Subsequent investigation identified a thermal short between the dewar forward closure cover and the VCS caused by thermal expansion of the solid nitrogen and is shown in Figure 1.

The depletion of the NICMOS dewar, coupled with the need for IR science on HST through Servicing Mission 4, prompted the HST Project to investigate a long term hardware solution to restore NICMOS scientific operations.¹ The requirements defined for the system focus on thermal performance and the dynamic disturbance impact to vehicle pointing performance. Specifically, the cooling hardware is required to remove heat from NICMOS (7 watts including parasitic heat loads) resulting in detector temperatures of < 75 K where effective imaging can occur (balance between quantum efficiency and dark current count). A thermal stability of ± 0.5 K is also required to eliminate the need for excessive calibration of the cameras. To maintain the current HST pointing performance of 7 milli-arc-second (mas) root mean square (rms), an allocation of 0.77 mas rms (induced vibration) for the cooler must be satisfied. These primary requirements excluded existing cooler technologies and pointed towards

emerging mechanical cryogenic coolers in development at Creare. The NICMOS Cryo Cooler (NCC), as part of the NICMOS Cooling System (NCS), was selected based on initial assessments of the gas bearings yielding very low vibration levels and the ability to meet the derived temperature level/stability requirements.

Figure 1 - NICMOS Cryogen Dewar



Design Background

The technology underlying the NCC had been under development at Creare for about 10 years prior to the start of design for the HST program.¹ In applying the technology to spacecraft cryocoolers; the following attributes drove the design:

- High thermal efficiency to minimize power usage and weight allocation
- High reliability over the lifetime of the mission
- Robust design to withstand the launch and on-orbit environments
- Low vibration signatures to minimize impact to spacecraft pointing
- Flexible packaging to meet mechanical interface requirements

Prior to the HST cooler, a single-stage, reverse-Brayton cycle Engineering Model (EM) cryo cooler was developed at Creare and delivered to the Air Force in 1994 for performance and endurance testing.^{2,3} The EM satisfied all specified requirements providing 5 watts of refrigeration while consuming 218 watts of input power at the thermal design point of 65 K resulting in an overall thermal efficiency of 8% versus the Carnot (ideal) cycle. In addition, the EM operated at temperatures as low as 35 K and at refrigeration loads up to ~10 Watts, demonstrating the range of potential applications from a single design.

The EM demonstrated high reliability and robustness in operating at the Kirtland AFB Phillips Laboratory in an adverse environment for more than 30,000 hours over its three-year life test program. Non-hermetic seals used in the test configuration permitted a constant influx of moisture to permeate into the system continually causing periodic degradation of turbine operation resulting in a reduced cooling capacity. Therefore, periodic gas cleaning was performed to restore the EM to original performance and testing was continued in order to study other potential life-limiting factors. No other limiting factors were identified and the testing was completed successfully.

By employing gas bearing turbomachine technology, a very low vibration environment is introduced by virtue of the small mass of the rotating shafts (~2 grams), the high rotational speeds (as great as 7500 revolutions per second (rps)), and the precision inertial balancing performed on the rotors. This low vibration design was integral in determining suitability for the HST NCC and was later characterized on the ground and during the Hubble Orbital System Test (HOST) mission. Measured vibration emittance levels demonstrate NCC compliance with the HST 7 mas rms jitter allocation, thus maintaining the current pointing accuracy of the HST.^{4,5}

Finally, flexible packaging allows a variety of configurations to suit the requirements of a unique spacecraft. The individual components may either be connected by lengths of tubing or tightly integrated into compact assemblies as required. Thermal interfaces for heat rejection or for cold loads may also be located at distances of up to a few meters from the cryo cooler without substantially affecting cryo cooler performance.

NCC Design

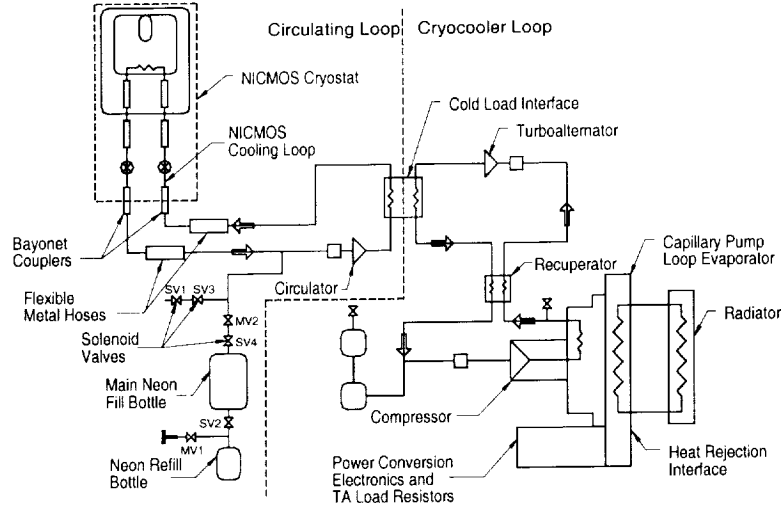
A schematic flow diagram of the NCS including the circulating loop, the cryocooler loop, and the Capillary Pumped Loop (CPL)/Radiator interface is shown in Figure 2.⁶ The NCC physical layout is shown in Figure 3. A centrifugal compressor driven by a three-phase inverter located in the Power Conversion Electronics (PCE), at rotational speeds up to 7300 rps, compresses the neon gas in the cryocooler loop. The work of compression is transferred through the compressor housing to the heat rejection interface (HRI) and is removed by the evaporator in the CPL and is rejected to the space environment at the radiator surface. The high-pressure gas from the compressor flows through a counter flow heat exchanger (Recuperator) where it is cooled by the low-pressure gas stream coming from the cold load interface (CLI). The high-pressure gas then flows through the Turboalternator where it is cooled by expansion to a lower pressure and spins the turbine shaft at speeds up to 4500 rps. A tiny permanent magnet inside the spinning shaft generates an electric current in the alternator coils that load the Turboalternator. The current is dissipated as heat in a set of load resistors attached to the Heat Rejection Interface (HRI). After leaving the Turboalternator, the gas flows through the CLI where the heat load from the circulation loop is transferred to the cryocooler loop. Completing the cycle, the cryocooler gas flows through the recuperator where it is warmed up before returning to the compressor inlet. At the nominal operating conditions in space, the compressor heat rejection temperature is about 290 K and the total heat load removed at the HRI is about 370 watts, including PCE electrical input power and a small amount of power from the Turboalternator.

The cryocooler loop is hermetically sealed to prevent leaks and to preclude the introduction of contamination by atmospheric gases. All tube joints and external boundaries on the compressor, recuperator, and turboalternator are either welded or brazed. The loop integrity was verified by X-ray inspection, proof pressure tests, and leak checks. Once filled with gas, the cryocooler loop was baked out to remove any remaining moisture and then sealed by closed valves and vacuum tight fittings secured for launch.

A miniature centrifugal circulator operating at a rotational speed of 1200 rps pumps cryogenic neon in the circulation loop between the CLI and the NICMOS cryostat. Heat transferred into the circulating gas at the NICMOS coil and from parasitic heat sources along the flow path is removed at the CLI. The neon absorbs a heat load of approximately 7 watts from the NICMOS coil, parasitic sources, and the circulator input power. The flexible fluid transfer lines from the circulation loop are connected to the existing bayonet fittings on the NICMOS cryostat panel via EVA action. Post-HST SM3B deployment, the loop will be filled with 16 grams of neon from a high-pressure storage tank. This provides an operating pressure of 4 atmospheres (ATM) at nominal design conditions in the circulation loop. A refill tank has

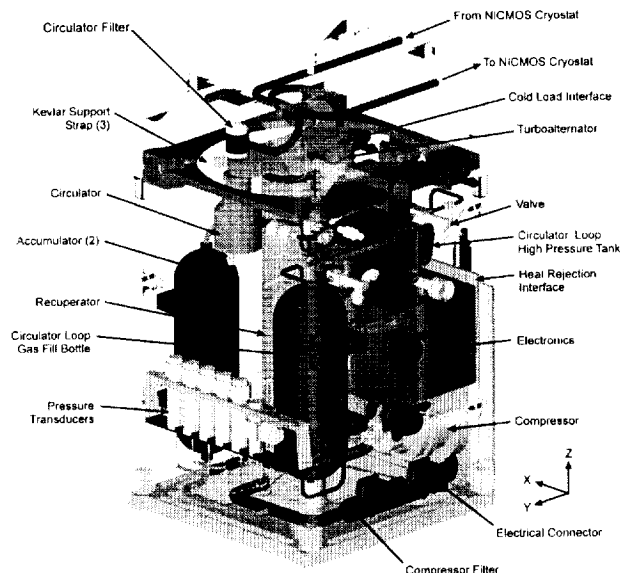
enough neon for one complete refill and can be used to periodically replenish gas in the circulation loop in the event of slow leakage through the bayonet O-ring seals.

Figure 2 - NCC Flow Diagram



The NCC bayonet fittings use a redundant pair of silicone O-rings selected for low-temperature sealing performance. However, silicone is also fairly permeable to atmospheric moisture and so exhaustive measures were implemented to ensure minimal impact from moisture contamination. These steps include a final pre-launch bakeout of the circulation loop at GSFC, combined with a continuous dry nitrogen purge environment, and nearly continuous evacuation of the circulation loop to remove moisture that may enter through the seals from the purge gas. The cooling coil in the NICMOS cryostat has been exposed to the vacuum of space for over 2 years since the previous servicing mission when the vent valves on the cryostat panel were opened. This has allowed frozen contaminants that may have been present to sublime and diffuse out of the coil. Any remaining moisture should have no effect on circulation loop performance.

Figure 3 - NCC Physical Layout



Hubble Orbital System Test

The NCS HOST testing, performed during STS-95 in October 1998, was a direct demonstration of on-orbit capabilities providing system validation and enhanced system knowledge beyond which can be accomplished through ground test means. The primary goal was to verify zero-g performance of the NCS with a major secondary goal of measuring the emitted vibration from the NCC. Development of the NCC included delivery of the internal machinery to the Goddard Space Flight Center (GSFC) from Creare in January 1998. The cryocooler was then integrated with its support structure, power and control electronics, instrumentation, and heat rejection system over the next several months in preparation for the HOST mission. Extensive environmental, thermal performance and flight qualification tests were conducted through the summer months of 1998. In October of that same year, and after a total development time of only 14 months, the NCC was flown on STS-95 as part of the HOST payload compliment. The zero-g performance of the NCC during HOST resulted in 185 hours of anomaly free operation satisfying the primary objectives. The operating time-line is summarized in Table 1.⁷ A minimum temperature of 72.65 K and stability of ± 0.1 K was reached using a surrogate representation of the NICMOS dewar called the NICMOS Cooling Loop Simulator (NCLS). The NCLS duplicates the internal flow passages in the NICMOS cryostat and includes shielding and heaters to allow controlled heat input to simulate the estimated NICMOS heat load. Figure 4 presents a photo of the NCC-NCLS interface for the HOST mission.

Table 1 - HOST NCC Operational Timeline

Mission Elapsed Time (day:hr:min)	Event
00:19:54	NCC Startup
00:19:54 to 02:23:41	Maximum power cooldown to first operating point
03:00:01 to 05:01:28	Set-point operation at cold plate temperatures from 76 K to 78 K
05:01:28 to 05:12:03	Reduced power idle operation
05:20:09 to 06:14:53	Compressor off during CPL deprime tests: circulator operating
08:08:04	Minimum cold plate temperature of 72.65 K
08:07:19 to 08:08:04	Cold stop/start test
08:12:50	Circulator disabled at end of warm-up
08:13:33	System power off

Figure 4 - NCC and NCLS in HOST Configuration



The NCC vibration measurements were obtained using two Space Acceleration Measurement Systems for Free-Flyers developed and built by the Glenn Research Center. Two sensor head units, one mounted to the base-plate and the other to the frame, each containing three accelerometers recorded data during various operational and non-operational periods to characterize vibration signatures. Results concluded that disturbances below 2 Hz produce the majority of contributions to HST jitter, while data resolution and corruption identified the need for further ground testing to reduce uncertainties attributed to mass participation and systematic errors.

Design Enhancements

Following the HOST mission, several modifications were made to subsystems in the NCC to improve efficiency and reliability.

Circulator

A post-HOST spin test of the NCC turbo machines resulted in a failure to start the circulator. Investigation revealed contact between the shaft and bearings with substantial damage to the anodized titanium surfaces most likely caused by moisture contamination present in the loop. In response, the shaft and bearings of the circulator were replaced with a new design incorporating a diamond-like-coating to improve margin against wear from contaminants, and improved bake-out/contamination control procedures were established to reduce the potential for contaminants in the loop.

Power Conversion Electronics

The entire PCE was redesigned to increase efficiency, provide a quieter power signal, implement operational changes, and increase sensor resolution. A unified power conversion design to drive the turbomachines was incorporated that regulates the alternating current and frequency for the motor increasing the overall power conversion efficiency. A new electromagnetic interference (EMI) filter was also added to improve the overall drive signal and changes to the signal processing were implemented to increase resolution problems encountered during HOST.

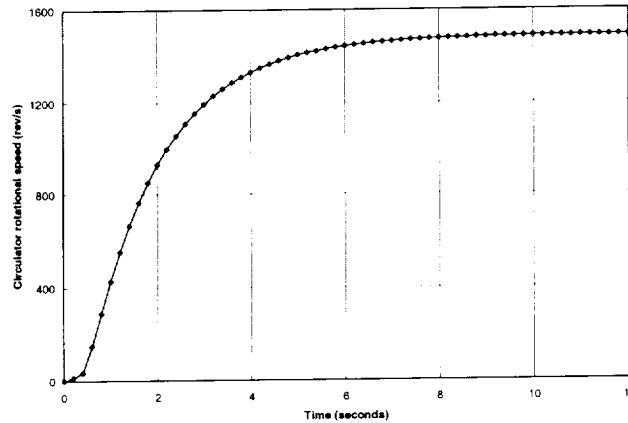
Thermal

The diameter of the flexible fluid transfer lines in the circulation loop was reduced to decrease radiative heat leak into the lines resulting in a decreased refrigeration load. In order to maintain low pressure drop and low input power with the reduced size lines, the circulator speed was reduced from 1500 rps to 1200 rps and the operating pressure level in the circulation loop was increased from 3 atm to 4 atm. These changes reduced the estimated heat load to the cryocooler by 0.25 watts to 0.5 watts.

Operations

The gas bearing wear mechanism is through contact between the shaft and bearings during startup and shut down operations. Since a faster acceleration on startup reduces the amount of time that the shaft and bearings are in contact, the startup time constant was reduced from 10 seconds to ~2 seconds by modifying the PCE inverter circuit to provide more current for startup as shown in Figure 5. For shutdown, the inverter drive circuit was modified to open the input leads to the motor allowing the gas bearings to continue to operate and the shaft to coast to a stop.

Figure 5 - Circulator Startup Time

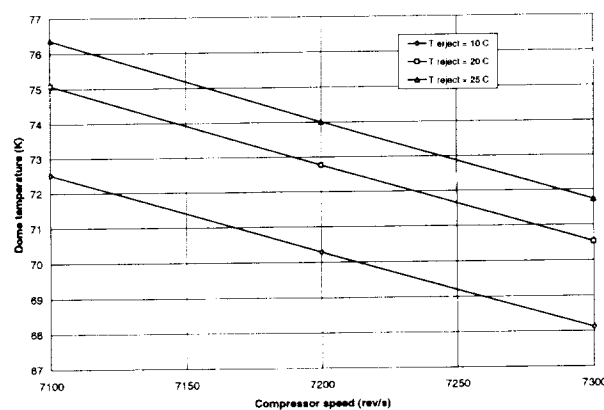


Performance and Reliability

The NCC thermal performance was characterized in several tests at GSFC and during the HOST mission. Each test produced variable conclusions, generally as a result of changes in the test configurations, devices used to simulate the NICMOS cryostat, or changes in instrumentation and telemetry. For each test, the overall performance of the cooling system was represented as the effective NICMOS “dome” temperature as a function of compressor speed and heat rejection temperature.¹ Test configurations incorporated features to simulate the thermal parasitic loads and the flow properties of the NICMOS cryostat. Figure 5 shows the estimated dome temperature given a total CLI load of 7 W as a function of the rejection temperature and the compressor speed. These tests were performed during October 2000 using a shunt loop to simulate the NICMOS cryostat loop.

The PCE modifications resulted in an input power reduction of 77 watts and an inverter efficiency of 95% at the maximum compressor operating speed of 7300 rps. The improved signal conditioning allows for better command and control of the NCC. The EMI filter changes resulted in an electronics box electrically “quieter” than any previously installed into the HST.

Figure 6 - Predicted NICMOS dome temperature with a total CLI heat load of 7 W



¹ The dome temperature is the temperature at the coiling coil inside the NICMOS cryostat. Since no sensor is located on the dome, there is no direct measurement of the dome temperature. However, based on analysis of the estimated parasitic heat load and distribution of the heat load, performance at the dome is calculated from measured temperatures near the CLI at the inlet and outlet to the circulation loop as $T_{\text{dome}} = 0.52 \times T_{\text{NICMOS in}} + 0.48 \times T_{\text{NICMOS out}}$.

The NCC reliability has been proven through extensive ground and flight test. The Compressor, Turboalternator, and Circulator have over 1900, 1400, and 800 hours of nominal run time respectively. Since incorporation of the improved bake-out procedures and the addition of the robust shaft/bearing coating, there have been no further incidents of anomalous circulator behavior. The PCE has operated successfully for over 2000 hours. All environmental testing, including three intensive, system level thermal vacuum tests were completed without incident in preparation for the SM3B installation.

Future Applications

Future National Aeronautics and Space Administration missions including the Terrestrial Planet Finder, Constellation-X, and the Next Generation Space Telescope will require the capability to reliably cool detectors and associated components to temperatures as low as 6 K for extended periods. Furthermore, the cooling load requirement ranges from a few watts to several hundred milli-watts, significantly less than that required for the NCC. Additionally, the long duration of these future missions, 5 to 10 years, make cryogenic dewars a heavy and undesirable option. The turbo-Brayton technology developed for NICMOS can be extended to these future, more-demanding applications. Current cooler technology development programs focus on smaller turbomachines and more compact recuperators compatible with the lower temperatures required for these missions. In addition to providing renewed life to NICMOS, the NCC serves as a technology milestone for future programs.

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